On relativistic effects and large scale cosmology

In collaboration with
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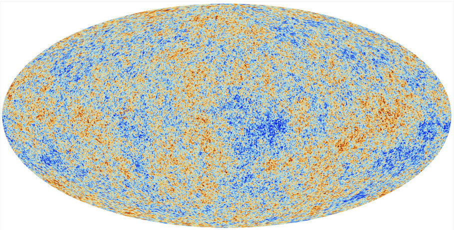
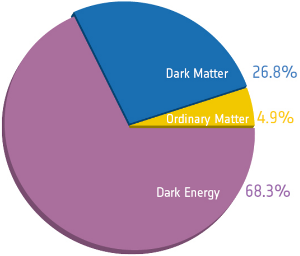
Cosmology at large and small scales
Universitá di Cagliari (7 marzo 2017)

Analysis of CMB anisotropies started the era of
PRECISION COSMOLOGY





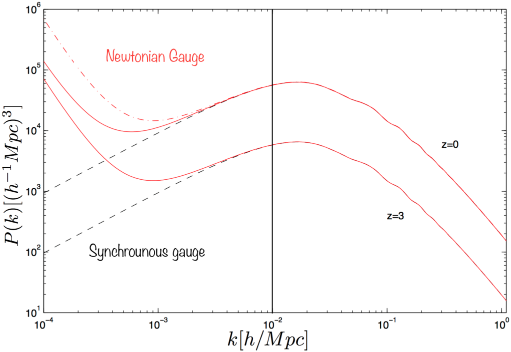
Credit: ESA and the Planck Collaboration.

- CMB offers a **2D** map of the universe

$\longrightarrow$ LSS will provide **3D** map of the distribution of galaxies: potentially richer information

NOT DIRECTLY OBSERVABLE

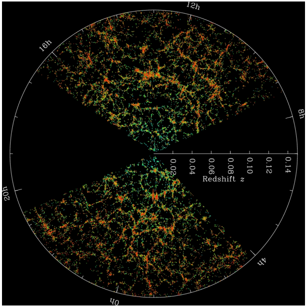
Credit: A. Challinor, A. Lewis (2011)



→ Assume a cosmology to convert observed redshift and angles into length scales.

→ Theoretical predictions are gauge-dependent.

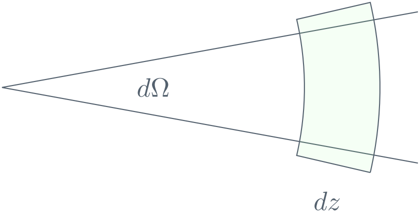
Observable in Galaxy Surveys



Credit: M. Blanton and the Sloan Digital Sky Survey.

Which **coordinates** do we observe?

- Redshift $\mathbf{z}$
- Direction of incoming photons $\mathbf{n} = (\theta, \phi)$



Galaxy Number Count

$$\Delta_{\mathrm{obs}}(\mathbf{n}, z) = \frac{N(\mathbf{n}, z) - \bar{N}(z)}{\bar{N}(z)}$$

- Relate the **observable** to the **local density** of galaxies

$$N(\mathbf{n}, z) = \rho(\mathbf{n}, z) \cdot V(\mathbf{n}, z), \qquad \bar{N}(z) = \bar{\rho}(z) \cdot \bar{V}(z)$$

$$\bar{\rho}(z) \approx \bar{\rho}(\bar{z}) + \partial_z \bar{\rho} \cdot \delta z$$

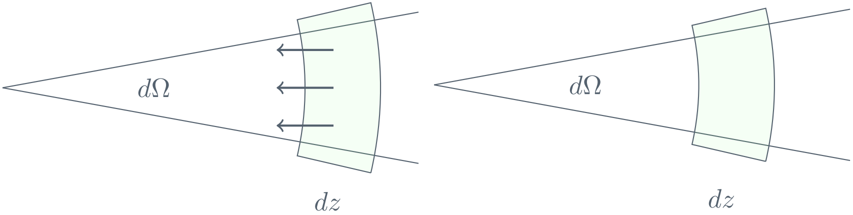
- In the **linear regime**

$$\boxed{\Delta_{obs}(\mathbf{n}, z) = \delta_g - \frac{3}{1+z}\delta z(\mathbf{n}, z) + \frac{\delta V(\mathbf{n}, z)}{\bar{V}}}$$

C. Bonvin, R. Durrer - *What galaxy surveys really measure* (2011)
A. Challinor, A. Lewis - *Linear power spectrum of observed source number counts* (2011)

Physical interpretation of δz

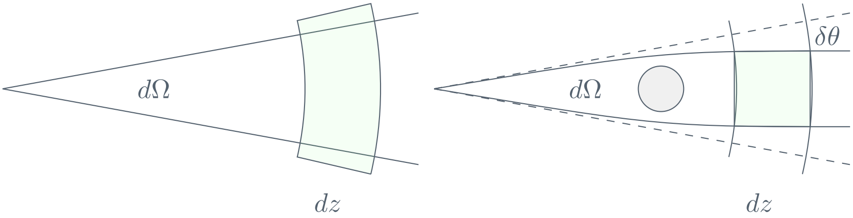
The distance we measure between us and the bin depends on the motion of the galaxies inside the bin



$\longrightarrow$ If in a redshift bin the galaxies are moving towards us with the same velocities, it will appear closer

Physical interpretation of δV

The direction of the incoming light is perturbed by the presence of intervening matter: fluctuation in the observed solid angle



Relation with velocity and metric perturbation

$$\Delta_{obs}(\mathbf{n}, z) = \boxed{\Delta_g + \frac{1}{\mathcal{H}(z)}\partial_r(\mathbf{V}\cdot\mathbf{n})}$$

Standard terms

$$+\left(5\ \boxed{s(m^*, z)}\ - 2\right)\int_0^{r(z)} \frac{r(z) - r}{2r(z)r}\Delta_\Omega(\Phi + \Psi)dr$$

Magnification bias!

$$+\left(\frac{\mathcal{H}'}{\mathcal{H}^2} + \frac{2 - 5s(m^*, z)}{r\mathcal{H}} + 5s(m^*, z)\right)(\mathbf{V}\cdot\mathbf{n}) - 3\mathcal{H}V$$

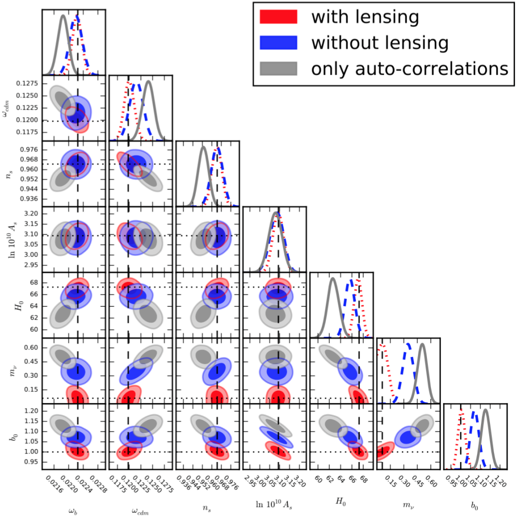
$$+(5s - 2)\Phi + (1 + 5s)\Psi + \frac{1}{\mathcal{H}}\Phi' + \frac{2 - 5s}{r(z)}\int_0^{r(z)} dr(\Phi + \Psi) +$$

$$+\left(\frac{\mathcal{H}'}{\mathcal{H}^2} + \frac{2 - 5s}{r(z)\mathcal{H}} + 5s\right)\left(\Psi + \int_0^{r(z)} dr(\Phi' + \Psi')\right)$$

Hierarchy $\longrightarrow$ $\sim \Delta_g$ $\quad \sim \frac{\mathcal{H}}{k}\Delta_g$ $\quad \sim \left(\frac{\mathcal{H}}{k}\right)^2 D$

Do we care about relativistic effects?

1. Neglecting relativistic corrections correction may bias the analysis



Credit: Cardona et al. (2016)

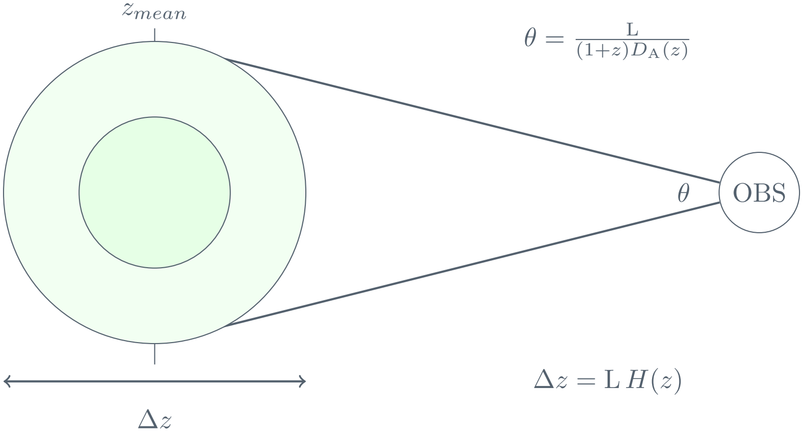
A model independent method for the Alcock Paczyński test

In collaboration with
Enea Di Dio, Matteo Viel, Carlo Baccigalupi, Ruth Durrer

Based on arxiv:1606.03114 - Published in JCAP

Purely geometric test of cosmic expansion

C. Alcock, B. Paczyński - *An evolution free test for non-zero cosmological constant* (1979)



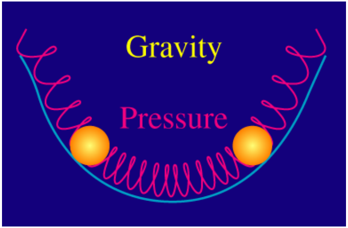
$$\theta = \frac{\mathrm{L}}{(1+z)D_{\mathrm{A}}(z)}$$

$$\Delta z = \mathrm{L}\, H(z)$$

The BAO feature in the galaxy correlation function can provide the scale L!

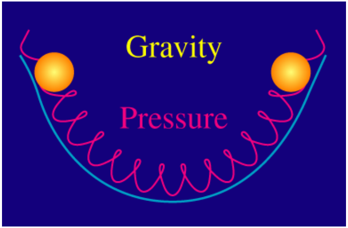
In the early universe baryons are coupled to photons:
single photon-baryon fluid

GRAVITY



Credit: Wayne Hu.

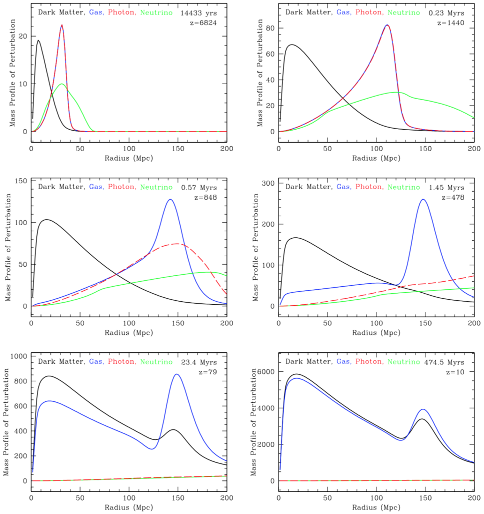
PHOTON PRESSURE



Credit: Wayne Hu.

Sound waves which propagates until recombination
imprint a feature in the correlation function at the sound horizon:
$\approx 150Mpc$

BAO feature in the correlation function



Evolution of an overdense region at a single point: **dark matter**, baryons, photons.

- The coupled fluid of photons and baryons move away from the dark matter at the centre (top panels)
- After recombination, photons continue propagating, baryons stay were they are (middle panels)
- Baryons fall into the gravitational potential generated by **Dark Matter** and viceversa. They share the same distribution (bottom panels)

D., Eisenstein, H. Seo, M. White - *On the Robustness of the Acoustic Scale in the Low-Redshift Clustering of Matter* (2007)

Current and future BAO measurements

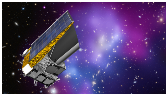
Sound horizon at the drag epoch is measured by **Planck** at the **0.3% level**

⟶ Use BAO scale as a standard ruler to test distance-redshift relation and map the expansion history

BAOs are one of the **main target of future generation of galaxy surveys**

BOSS

DESI & Euclid



Current measurements

- From BOSS (the Baryon Oscillation Spectroscopic Survey)

1% precision

Next generation of surveys

- Euclid Spacecraft, launch planned for 2020
- DESI (Dark Energy Spectroscopic Instrument), starting in 2018

0.1% precision

Overview & Notation

OVERVIEW

1. Test a model independent method for the AP test

   (Montanari and Durrer, 2012)

2. Systematic effects due to lensing and galaxy bias
3. Window function shift
4. Statistical uncertainties (shot-noise and cosmic variance)

NOTATION

$$\Delta_{\text{obs}}(\mathbf{n}, z) = \boxed{\Delta_g} + \Delta_{\text{RSD}} + \Delta_\kappa + \cancel{\Delta_{\text{rel}}},$$

- Redshift space distortion

$$\Delta_{\text{RSD}}(\mathbf{n}, z) = \boxed{\frac{1}{\mathcal{H}(z)}\partial_r(\mathbf{V}\cdot\mathbf{n})} + \left(\frac{\mathcal{H}'}{\mathcal{H}^2} + \frac{2}{r\mathcal{H}}\right)(\mathbf{V}\cdot\mathbf{n}) - 3\mathcal{H}V$$

- Lensing Convergence

$$\Delta_\kappa = (5 \underbrace{\boxed{[s(m^*, z)}}_{=0} - 2)\int_0^{r(z)} \frac{r(z) - r}{2r(z)r}\Delta_\Omega(\Phi + \Psi)dr$$

Methodology

1. Compute the angular power spectrum
   - Run CLASSgal for our fiducial cosmology (Planck + external data)

     E. Di Dio, F. Montanari, J. Lesgourgues, R. Durrer (2013)
2. Compute the correlation function in both **radial** and **transverse** direction from the redshift dependent angular power spectra
3. Use a **phenomenological model** for the correlation function

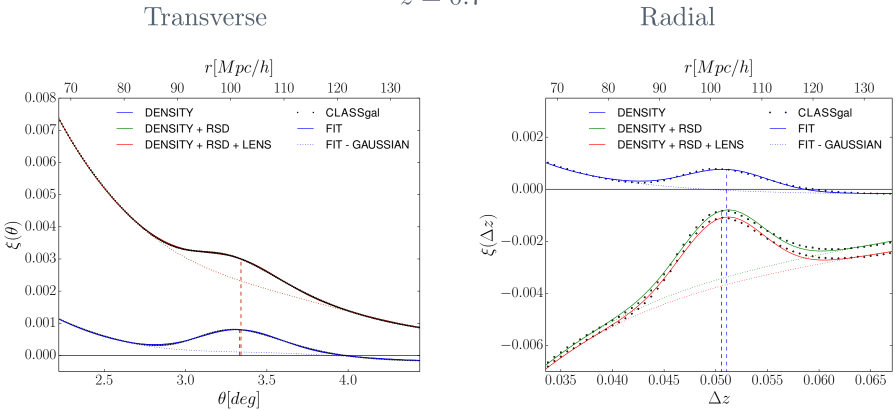
$$\xi(x) = A \cdot e^{-(x-x_{\mathrm{FIT}})^2/2\sigma^2} + \sum_{n=0}^{N} K_n \cdot x^n,$$

4. Estimate the peak position Δz_{FIT} and θ_{FIT}
5. Compare $F_{\mathrm{AP}} = \Delta z_{\mathrm{FIT}}/\theta_{\mathrm{FIT}}$ to its expected value

$$F_{\mathrm{AP}} = (1+z)H(z)D_{\mathrm{A}}(z)$$

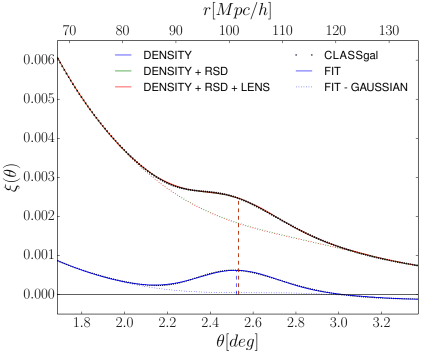
Results: RSD & Lensing

$z = 0.7$

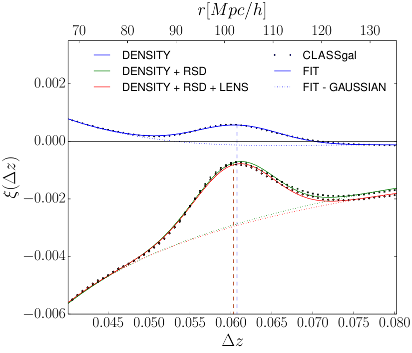


$z = 1$

Transverse

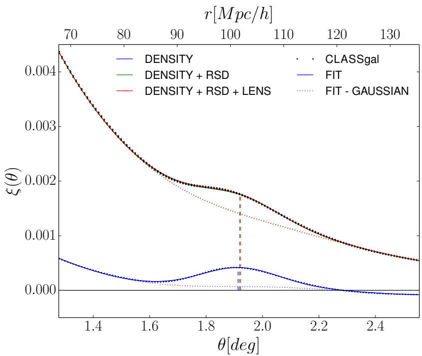


Radial

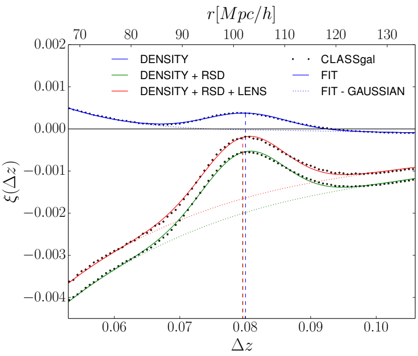


$z = 1.5$

Transverse

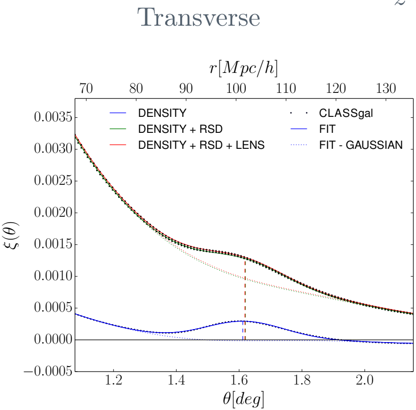


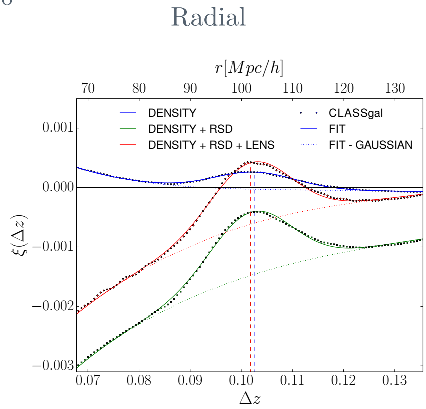
Radial



RSD & Lensing

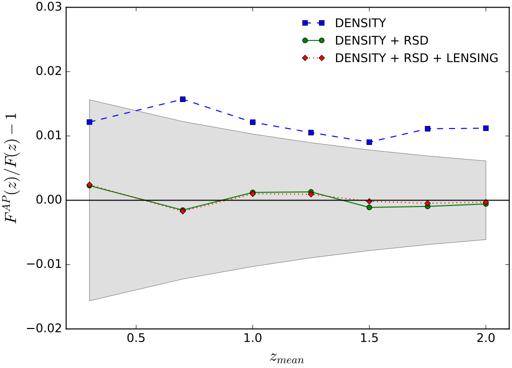
$z = 2.0$





ONLY DENSITY: shift in the estimated peak position $\approx 0.5\%$ in both directions
plus LENSING: change in the amplitude of radial correlations, but the peak positions is not affected in both directions

Consistency Test



The shaded region shows the errors computed from the resolution in Δz and θ

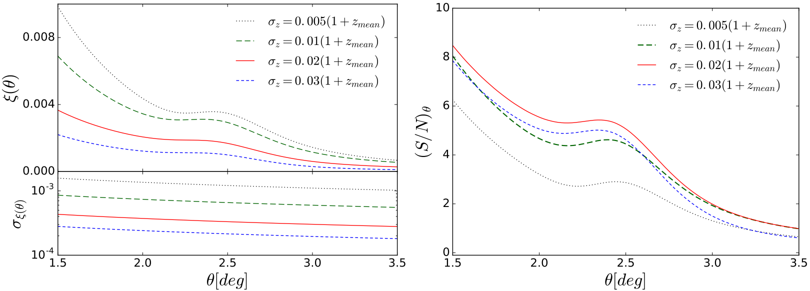
When ONLY DENSITY: $\sim 1\%$ offset between the expected and computed value of F_{AP}

LENSING does not affect the AP test

Window function

$\longrightarrow$ Need spectroscopic resolution for radial BAO
$\longrightarrow$ **Maximize** S/N choosing optimal redshift binning in the transverse

Example: Euclid Survey - $z = 1$



Optimized window function for 3 spectroscopic survey

Euclid SKA DESI

$$\sigma_z = 0.02(1 + z_{mean})$$

$\sigma_z = 0.02(1 + z_{mean})$

OFFSET BETWEEN 3% AND 5%

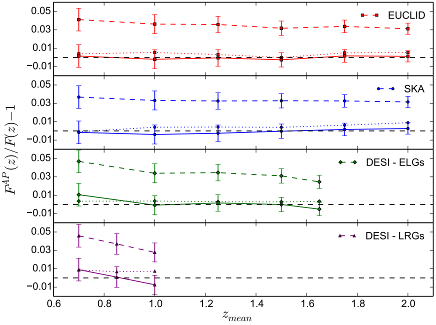
Model for the AP function (Montanari and Durrer, 2012)

$$F_{AP}(z_{mean}) = \frac{\Delta z_{BAO}}{\theta_{BAO}} \sqrt{1 - \gamma \cdot \left(\frac{\sigma_z}{\Delta z_{BAO}}\right)^2}$$

We estimate γ by minimizing

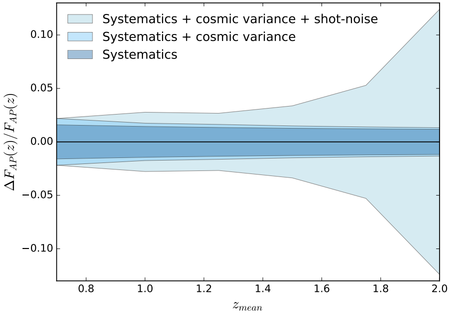
$$\chi^2 = \sum_i \left(\frac{F_{AP}(z_i) - F_{th}(z_i)}{\Delta F_{AP}(z_i)}\right)^2$$

	Bias	γ
EUCLID	$\sqrt{1+z}$	0.166
SKA	$c_4 \exp(c_5 z)$	0.161
DESI - ELGs	$0.84/D(z)$	0.151
DESI - LRGs	$1.7/D(z)$	0.154



Impact of the shot-noise

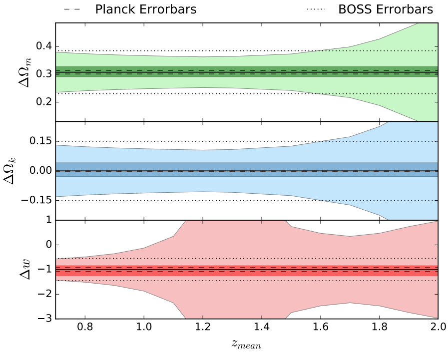
EUCLID-LIKE SURVEY



Statistical error is dominated by **cosmic variance** at **low redshift**

Shot-noise is the major contributor at **high redshift**

ERRORS ON PARAMETERS



Light shaded region ⟶ Error from one measurement

Dark shaded region ⟶ Error from 10 independent measurements

Conclusions

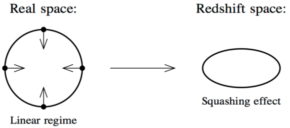
- We tested the possibility of performing the AP test in a **model independent** way
- Gravitational lensing **does not affect** the estimation of the BAO peak position
- The parametrization introduces an **extra 1% error** due to uncertainty on galaxy bias
- We computed the **correction to the projection effect**, introduced by a window function in the transverse direction
- **The shot-noise has a significant impact on the error**
  - Cosmic variance dominates the statistical error at low z
  - The shot-noise is the major contribution at high z

Optimal survey for relativistic distortions in the cross-correlation 21cm - galaxies

In collaboration with
Enea Di Dio, Eleonora Villa, Matteo Viel

WORK IN PROGRESS

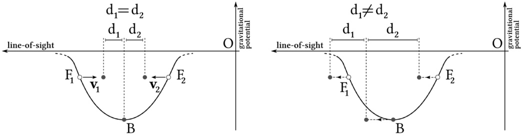
- Anisotropy induced by peculiar velocities



Credit: A. J. S. Hamilton, 1997

- Asymmetry induced by relativistic distortions

Example of Gravitational Redshift



Credit: C. Bonvin et al., 2014

→ **Imaginary part** of the Fourier space power spectrum
(Patrick McDonald, 2009)

→ **Dipole** of the correlation function (C. Bonvin et al., 2014)

Multiple expansion of the CF and $P(k)$

- Relation correlation function - power spectrum multiples

$$\xi_\ell^{AB}(d, z_1, z_2) = (-i)^\ell \int \frac{k^2 dk}{2\pi^2} P_\ell^{AB}(k, z_1, z_2) j_\ell(k\, d),$$

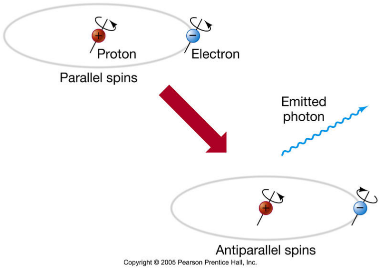
- where

$$P_1^{AB} = (-i)\left\{\left(\frac{2}{r\mathcal{H}} + \frac{\dot{\mathcal{H}}}{\mathcal{H}^2}\right)(b_B - b_A) + \left(1 - \frac{1}{r\mathcal{H}}\right)[3(s_A - s_B) + 5(b_B s_A - b_A s_B)]\right\} f \frac{\mathcal{H}}{k} P_m(k)$$

$$P_3^{AB} = (2i)\left(1 - \frac{1}{r\mathcal{H}}\right)(s_B - s_A) f^2 \frac{\mathcal{H}}{k} P_m(k)$$

$$\left(\frac{S}{N}\right) = f(\text{bias, magnification biases, evolution bias, volume of the survey...})$$

NOT ALL INDEPENDENT



Intensity mapping

Measure the integrated radio emission from unresolved gas clouds

Many planned low-z 21 cm IM experiment

(the Canadian Hydrogen Intensity Mapping Experiment(CHIME), Hydrogen Intensity and Real-time Analysis eXperiment (HIRAX) , BAO from Integrated Neutral Gas Observations (BINGO), Square Kilometer Array (SKA-mid)...)

Observed quantity:

$$\Delta_{T_b}(z, \mathbf{n}) \equiv \text{fluctuation in the 21 cm brightness temperature}$$

- Computed at first order in perturbation theory (A. Hall et al., 2013)
- Equivalent to the number count, with NO LENSING: $\rightarrow s_{HI} = 0.4$

Halo based method

Villaescusa-Navarro et al., 2014

- Abundance of neutral hydrogen inside halos

$$\Omega_{\rm HI}(z) = \frac{1}{\rho_c^0}\int_0^\infty n(M,z) M_{\rm HI}(M,z) dM,$$

  $n(M,z) \rightarrow$ Tinker halo mass function at z (Tinker et al., 2008)
  $M_{\rm HI}(M,z) \rightarrow$ average HI mass inside a halo of mass M at redshift z

- Shot-Noise (From *Castorina and Villaescusa-Navarro, 2016*)

$$P_{\rm SN}(z) = \left(\frac{1}{\rho_c^0 \Omega_{\rm HI}(z)}\right)^2 \int_0^\infty n(M,z) M_{\rm HI}^2(z) dM,$$

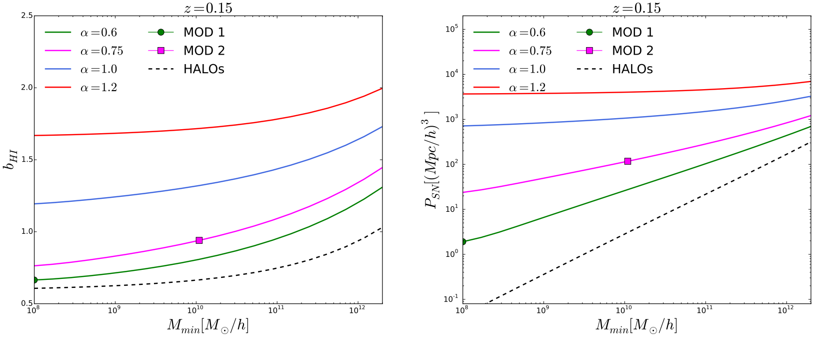
- HI bias

$$b_{\rm HI}(z) = \frac{1}{\rho_c^0 \Omega_{\rm HI}(z)}\int_0^\infty n(M,z) b(M,z) M_{\rm HI}(z) dM,$$

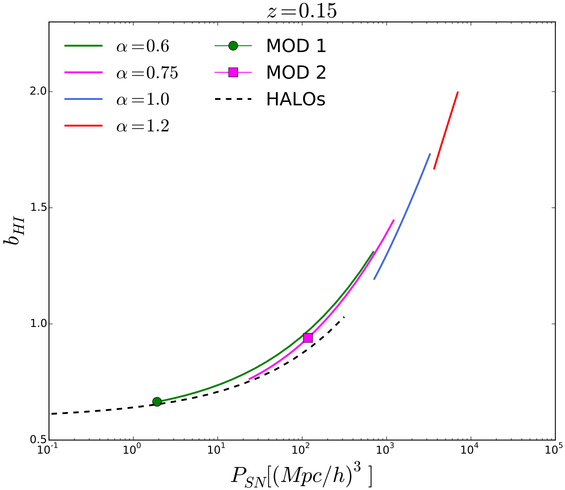
Modeling HI distribution

$$M_{\mathrm{HI}}(M,z) = \mathrm{C} \cdot (1 - Y_p)\frac{\Omega_b}{\Omega_m}\exp\Big[-(M_{\min}/M)\Big] \cdot M^{\alpha}$$

(From *Castorina and Villaescusa-Navarro, 2016*)



Bias VS shot-noise

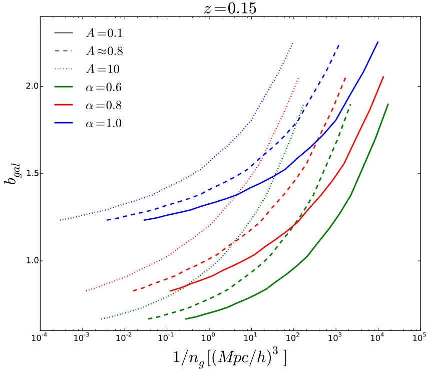


Modeling Galaxies

We model the average number of galaxies within a halo of mass M as

$$N_{\rm av}(M) = \begin{cases} 0 & \text{if } M \leq M_{\rm min} \\ A \cdot \left(\frac{M}{M_{\rm min}}\right)^{\alpha}, & \text{if } M > M_{\rm min} \end{cases}$$

Bias vs Shot-Noise



Preliminary S/N analysis in Fourier space

MOD 1

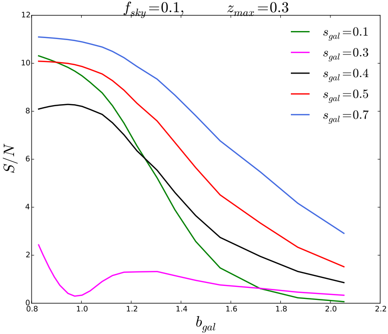
$M_{\rm min} = 10^8$ and $\alpha_{\rm HI} = 0.6 \longrightarrow$

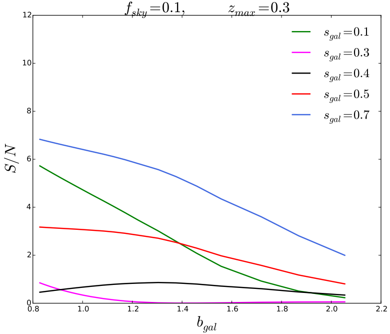
$b_{\rm HI} = 0.67, \qquad P_{\rm SN} \sim 1 (Mpc/h)^3$

MOD 2

$M_{\rm min} = 10^{10}$, $\alpha_{\rm HI} = 0.75 \longrightarrow$,

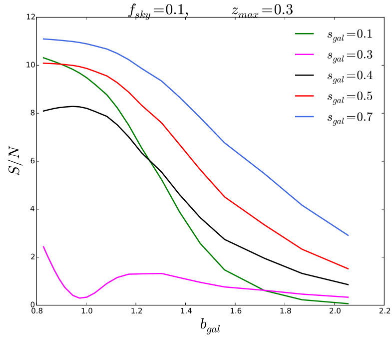
$b_{\rm HI} = 0.96, \qquad P_{\rm SN} \sim 100 (Mpc/h)^3$



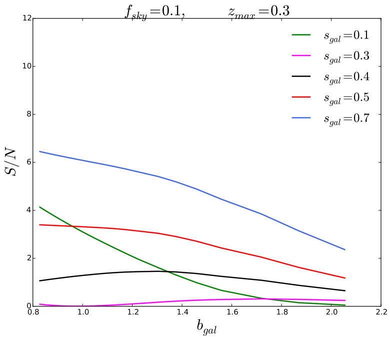


Preliminary S/N analysis in Fourier space

NO INTERF. NOISE



+ INTERF. NOISE



Work in Progress

- Generalize the analysis to the configuration space, including full covariance and interferometer noise
- Modeling the luminosity function for specific galaxy surveys
- ...
- ...

Thanks for your attention!

Correlation function and angular power spectrum

Compare the galaxy number count in different bins

- Correlation function

$$\xi(\theta, z_1, z_2) = \langle \Delta_{\rm obs}(\mathbf{n}_1, z_1)\Delta_{\rm obs}(\mathbf{n}_2, z_2)\rangle\,, \qquad \cos\theta \equiv \mathbf{n_1}\cdot\mathbf{n_2}$$

- Angular power spectrum

$$\Delta_{\rm obs}(\mathbf{n}, z) = \sum_{\ell m} a_{\ell m}(z) Y_{\ell m}(\mathbf{n}), \qquad a_{\ell m} = \int d\Omega_{\mathbf{n}} Y^*_{\ell m}\Delta_{\rm obs}(\mathbf{n}, z)$$

$$C_\ell(z_1, z_2) = \langle a_{\ell m}(z_1) a_{\ell m}(z_2)\rangle$$

Transverse and Radial correlation function

- Compute $\xi(\theta, z_1, z_2)$ from $C_\ell(z_1, z_2)$

$$\xi(\theta, z_1, z_2) = \frac{1}{4\pi}\sum_{\ell=0}^{\infty}(2\ell+1)C_\ell(z_1, z_2)P_\ell(\cos\theta),$$

- **Transverse** correlation function

$$\xi_\perp(\theta, z_{\rm mean}) = \frac{1}{4\pi}\sum_{\ell=0}^{\infty}(2\ell+1)C_\ell(z_{\rm mean}, z_{\rm mean})P_\ell(\cos\theta)$$

- **Radial** correlation function

$$\xi_\parallel(\Delta z, z_{\rm mean}) = \frac{1}{4\pi}\sum_{\ell=0}^{\infty}(2\ell+1)C_\ell\left(z_{\rm mean} - \frac{\Delta z}{2}, z_{\rm mean} + \frac{\Delta z}{2}\right)P_\ell(1)$$